Investigation of Stirling Engine Power Sources for Diver Propulsion Vehicles

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LONG-TERM GOALS

The long-term goal of this research is to develop a Stirling cycle power source for use in Very Shallow Water Mine Countermeasure (VSW MCM) Detachent diver propulsion. Current Diver Propulsion Vehicles (DPV) use batteries to power an electric motor, which limits duration and speed. In order to successfully operate in VSW theaters, an air independent, reliable, power source must be developed.

OBJECTIVES

This effort was directed at assessment of Stirling engine technologies to meet the performance goals of a medium duration, high speed, high payload DPV for VSW MCM applications. This survey was restricted to engine systems that were commercial off the shelf (COTS) or could be reasonably modified (MOTS) in order to meet the application requirements.

APPROACH

This investigation was broken down into two phases. The first phase involved the development of performance requirements to meet the anticipated DPV requirements of the VSW MCM mission. The second phase involved a commercial survey and rating of COTS and/or MOTS systems to meet the developed requirements.

WORK COMPLETED

In order to determine the power output required by the Stirling propulsion system, a thorough examination of state-of-the-art underwater dive vehicles had to be incorporated with the DPV performance requirements stated in the Performance Specification for Diver Propulsion Vehicle solicitation N00174-98-R-0092 attachment 2 dated 14 December 1998. It was then necessary to compile information on current two-diver systems to determine the power requirements to propel a hydrodynamically efficient underwater craft meeting DPV speed requirements. The DPV will be limited to transition to the VSW zone and not into unknown/uncleared VSW areas. Use will also support post assault clearance from cleared lanes to the beach. In order to perform these tasks, the Stirling propulsion system must enable the DPV to meet the following general system requirements:

- **Carrying Capacity**. The DPV shall carry at least two fully equipped VSW MCM divers and additional gear.
- **Range**. The DPV shall have a range of six nautical miles at a cruising speed of two knots. It is desirable that the DPV be capable of attaining a short duration operating speed of six knots.
- **Operating Depth**. The DPV shall be capable of normal operations at depths ranging from 0-60 feet of seawater (FSW).

Research into currently available underwater vehicles of appropriate size, operated with two divers, propelled underwater at speeds of six knots, was undertaken. The purpose was to determine what the overall power requirements for the Stirling power system should be. The most efficient platform types discovered are the vehicles listed below that are designed to be powered by one human cyclist in a flooded underwater vehicle that housed two divers. The maximum continuous output by the human cyclist during race durations is ½ horsepower (375 watts). The human powered submarine vehicle body shape and propeller could be used for the Navy DPV with a ½ horsepower engine replacing the need for human power. With many successful vehicle designs available, we were able to conclude that any one of vehicles could be copied and modified to meet the Navy DPV requirements. Table 1 lists vehicles that competed in two-diver speed trials at the 1996 World Submarine Invitationals.

Table 1. Human Powered Vehicle Speeds

Sub name/Team	Speed (kts)
Substandard / Aero-Environment	6.4
Omer / Ecole de Technologie,Canada	6.5
Torpedo III / Tennessee Tech	6.1
FAU-boat / Florida Atlantic Univ.	6.0
Subjugator / Batelle Industries	5.9

Based on the human powered vehicle information, it was determined that a ½ hp (375 watt) Stirling engine, as a minimum, would be sufficient to provide propulsion for the VSW MCM DPV. This would be with two divers at speeds up to six knots for a duration that would allow the DPV to cover six nautical miles. However, in order to handle larger payloads (equipment), 1 hp would be desirable.

A market survey was conducted to determine the availability of COTS equipment to meet the general Stirling engine requirements. It was discovered that Stirling engine technology had reached a stage of development that could be utilized in the VSW MCM mission scenarios requiring a DPV or a UUV. However, modifications to the COTS engines would be required for underwater use.

The survey was conducted by searching through current Stirling engine patents, Stirling engine conference proceedings, Stirling engine news publications, Internet searches, and visits to prospective Stirling engine manufacturers. There are over 1000 Stirling engine related patents identified from 18 countries. This list was reviewed to identify potential manufacturers for the DPV Stirling engine. A detailed look at patent abstracts that appeared to be applicable was undertaken to identify potential manufacturers. The Stirling engine manufacturers whose engines appeared to be at a development stage that could be utilized by the Navy were visited to determine the availability and suitability of their engines for the DPV application.

The following is a list of available Stirling engines with findings from on-site visits of each manufacturer.

DEKA Research and Development Corporation
340 Commercial Street
Manchester, NH 03101

Navy engineers attended a demonstration of the Stirling engine produced by DEKA in Manchester, New Hampshire on January 21, 1999. Two beta units were running indoors at their facility. Each unit consisted of a Stirling engine and rotary DC generator hermetically sealed in the same housing. One unit was running in an office space and the other was in a laboratory space. Both of the units burned propane and exhausted their combustion by-products into the surrounding environment. The first unit's electrical output was attached to a load bank of light bulbs such that the load could be varied through a switch box. Indicated electrical output for the first unit was 90V at 480 watts with an average helium pressure of 320 psi. This unit did not have an hour meter. Indicated electrical output for the second unit was 90V at 100 watts with an average helium pressure of 220 psi. The second unit had an hour meter that read 180 hours. The control system for both units was at the breadboard stage of development.

Sigma Elektroteknisk A.S.
P.O Box 58, N-1550
Holen, Norway

Technical information on this engine is limited to that provided by the manufacturer through correspondence. No site visits were made.

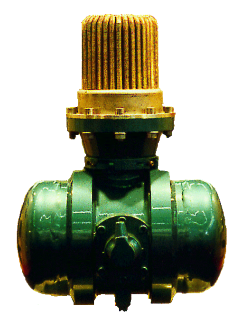

Figure 1. Sigma Elctroteknisk Engine

Whisper Tech Ltd.
P.O Box 13 705
Christchurch, New Zealand

Figure 2. Whisper Tech Engine

A Navy representative attended a demonstration of the Stirling engine produced by Whisper Tech in Christchurch, New Zealand on February 9, 1999. Twelve beta units were available for inspection and ready for shipping. Three units were running in their lab space. Two of the units were burning kerosene fuel. Each unit consisted of a Stirling engine and a rotary permanent magnet alternator hermetically sealed in the same housing. One of the engines burned butane and was outfitted with an AC alternator hermetically sealed in the same housing. Exhaust emissions were such that the kerosene engines had to be exhausted outdoors. Each DC unit was outputting 700 watts of continuous 12V DC power. The units operate at approximately 1500 rpm with an average internal nitrogen gas pressure of 20 bar. (294 psi). The noise level was high enough to impede normal conversation with the unit's fiberglass cover removed, however, the noise level was measured at 44 db from a distance of seven meters with the cover in place. Each DC unit included a marine heat exchanger and an alternator cooling system. The control system is fully automated and micro-controlled with load management capabilities.

Stirling Technology Company
4208 West Clearwater Ave.
Kennewick, Washington

A Navy representative attended a demonstration of the Stirling engine produced by Stirling Technology Company in Kennewick, Washington on March 30, 1999. Eight units were running indoors at their facility. Each unit consisted of a Stirling engine and linear DC generator sealed in the same housing. Three units were running in an office space and the others were in a laboratory space. All of the units burned propane and exhausted their combustion by-products into the surrounding environment. The demonstration unit's electrical output was attached to a battery charger and battery. Indicated electrical output for the demonstration unit was 89V at 250 watts. The average helium pressure of the engine/ alternator housing was 730 psi. The demonstration unit had an hour meter that indicated over 5000 hrs. The indicated electrical outputs varied on the units being tested. None were over 300 watts. The size of the control system is currently 9” x 17” x 19” and includes a battery and charger. A smaller control system is currently being tested.

Table 2. Engine Characteristics

	Sigma	WhisperTech	Stirling Technologies	DEKA
Configuration	Single cylinder	Four cylinder, double acting piston, wobble yoke drive,	Free-piston linear alternator	Single power piston with separate displacer piston
Power Output	1000 - 3000 watts electrical (vary working gas pressure)	750 watts electrical, 5000 watts useable heat	350 watts usable continuous DC	400 watts usable continuous DC
Size	600mm x 400mm x 350mm (23.6” x 15.7” x 13.7”)	450mm x 500mm x 650mm (17.7” x 19.7” x 25.6”) (includes fiberglass enclosure)	23” x 8” dia.	1850 in3
Weight Air	165 lbs. (includes pressurized enclosure)	198 lbs. (Includes fiberglass enclosure)	42 lbs.	36 lbs.
Fuel	Propane or natural gas	Diesel, Kerosene	Propane	Propane
Fuel Consumption	Unknown	Approximately 1 liter per hour	Unknown	Approximately 1 kWh per 1 lb. Fuel
Efficiency	30%	25%	22%	20-25%
Noise Level	Unknown	4 dB at 7 meters	negligible	60 dB at 3 meters
Emission Level	Unknown	CO < 300 ppm	CO < 20 ppm	CO < 86 ppm
Working Fluid	Unknown	Nitrogen	Helium	Helium
Working Gas Pressure	Unknown	294 psig	730 psig	25 atm
Materials	Aluminum	Cast aluminum, steel	Steel, copper, aluminum	Nickel alloy, aluminum, graphite pistons
Availability	June 1999, demonstration to be scheduled	3 months from receipt of order	4 months after receipt of order in current configuration	Production model available Dec. 1999, Underwater additional 9 months.
Cost	$ 40K U.S.	$ 50K U.S.	$ 55K U.S.; kerosene/ underwater additional 110K & 9 months.	Negotiable

All engines currently available burn kerosene or propane. The combustors operate at one atmosphere with the appropriate fuel and air mixture ignited in an enclosed heat exchanger and exhausted to ambient surroundings. To prepare the engines to run underwater, a combustion gas recirculation (CGR) system is necessary. The CGR system will reduce the volume of gas required to run the engine underwater and reduce exhaust to avoid detection. Air in the combustion process will be replaced with pure oxygen to reduce gas storage requirements. The adiabatic flame temperature resulting from combustion of 100% oxygen and propane or kerosene fuel exceeds those allowable for combustor materials. Recirculation of the inert combustion by-products reduces the flame temperature to an acceptable value. The CGR system also allows the increase in combustor operating pressure to slightly above ambient for underwater operations. The Stirling engines currently available have linear or rotary alternators hermetically sealed in the engine housings. The alternators produce either AC or DC electrical power which can be supplied directly to propulsion motors and battery storage. The power output of all these engines can be significantly improved by increasing the pressure of the working fluid. However, this will most likely have an impact on engine reliability and life.

Each power unit was rated on performance in the categories listed below. Objective data was used in every possible incidence. A score of 10 in a category represents an area where no additional effort will be required for that category to be acceptable. A score of 0 in a category means a complete redesign of that category is required.

Categories:

- **Manufacturability:** Degree that a unit is ready for manufacture at the beta prototype stage for use in an air environment upon receipt of order. (None of the power units are 100% developed for mass production.)
- **Reliability:** Subjective data based on Navy personnel witnessing product demonstrations of running beta prototypes in an air environment.
- **Resources:** The ability of the manufacturer to deliver, support, and modify the power unit to meet the Navy's current requirements running underwater.
- **Combustor:** Includes: combustor housing, combustor seals, burner, air delivery system, fuel delivery system, and exhaust system. Score indicates the degree of modification necessary to prepare this portion of the propulsion system to be functional underwater.
- **Main Engine:** Focus is on the pressurized portion of the Stirling engine (crankcase, pistons, piston cylinders, piston seals, displacers, displacer cylinders, displacer seals, connecting rods, bearings). Score indicates the degree that of modification necessary to prepare this portion of the propulsion system to be functional underwater.
- **Control System:** Includes fuel, air flow, electrical output, user interface, safety features, and packaging. Score indicates the degree of modification necessary to prepare this system to be functional underwater.
- **Exhaust:** Score indicates the degree that exhaust is harmful to operators in an enclosed environment.
- **Electrical Power Output:** Power output, design reliability.

Table 3. Stirling Engine Ratings

Category	Whisper Tech	Stirling Technologies	D.E.K.A.
Manufacturability	10	10	9
Reliability	10	10	10
Resources	10	10	10
Combustor	5	7	7
Main Engine	10	10	10
Control System	9	8	7
Exhaust	4	10	10
Electrical Power Output	10	8	9
Totals	68	73	72

IMPACT/APPLICATIONS

Successful transition of this development will allow for the development of a diver propulsion system that permits safer and more effective missions in currently prohibitive theaters of operation. A high capacity, hydrocarbon fueled DPV allows for diver insertions from greater standoff distances, decreasing diver detection risk, and permitting alternate insertion platforms (ASDS, submarine).

The non-magnetic capability of this system will lead to a propulsion vehicle that can operate safely in waters where magnetic influence mines may be present. This would fill a current gap for both the Explosive Ordnance Disposal (EOD) components and also for the Special Warfare forces operating in a littoral environment.

TRANSITIONS

The investigation conducted under this effort could lead ultimately to the development of a multi-function, long range, LPI / LPD diver capability. Alternate used of this propulsion technology could be in Remotely Operated Vehicles (ROV) for shallow water mine countermeasures.

RELATED PROJECTS

The Program Executive Office (PEO) Mine Warfare is currently investigating commercially available DPVs platforms for double diver applications. United States Special Operations Command (USSOCOM) is also searching for commercially available vehicles as part of their Swimmer Transport Device (STD) program.